Thermally-Induced Dynamics of Spacecraft Structures

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Overview

- Introduction
- Analytical studies
  - Orbital eclipse heating
  - Appendage thermal-structural response
  - Satellite dynamics response
- Experimental studies
  - Test set-up
  - Representative test results
  - Analysis of experiments
- Summary

Introduction

- What are thermally-induced dynamics?
  - Structural dynamics resulting from time-varying temperature distributions typically initiated during orbital eclipse transitions.

- What are the consequences of the disturbances?

  Due to conservation of angular momentum, motions of flexible structures result in rigid body rotations of the entire satellite leading to pointing errors and upsetting stability.

- What types of spacecraft structures are typically susceptible?
  - Booms (particularly STEM-type)
  - Solar arrays (rigid panel and flexible blanket)

Motivation

Hubble Space Telescope's Flutter Will Require Solar-Panel Fix

By Kathy Sawyer
Washington Post Staff Writer

The Hubble Space Telescope's continuing jitter is proving unexpectedly complicated to fix, and the European-built solar panels that are causing it will have to be repaired or replaced by spacewalking shuttle astronauts, according to Hubble engineers.

The flutter is apparently caused when the spacecraft reacts to abrupt temperature changes that occur each time the $1.5 billion orbiting observatory passes between shadow and sunlight. It has been the Hubble's most serious problem other than the major manufacturing flaw discovered in its primary mirror in June.

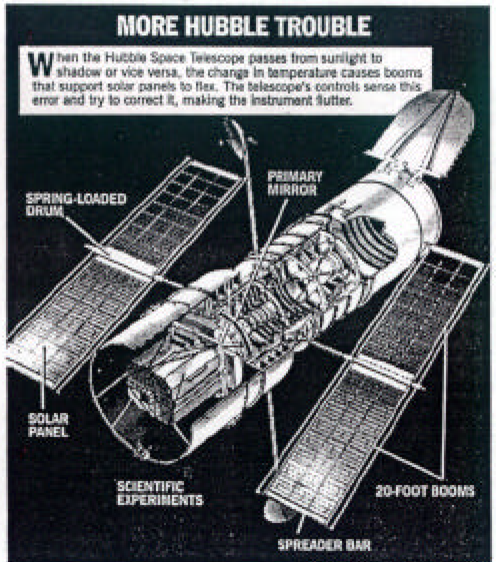
The motion is so slight that it would not matter in most spacecraft whose work does not require the precision of the Hubble's.

The telescope has already begun to produce significant scientific data and images of the heavens, although it is still in its check-out phase, and scientists have been able to work around the jitter problem. But if it continues indefinitely, officials say, it will reduce the telescope's precious observation time and strain resources on the ground trying to compensate for it.

For six to 10 minutes out of each 96-minute orbit, the booms that support the telescope's 40-foot solar "wings" bend as temperatures rise or fall by 82 degrees Fahrenheit within 57 seconds, according to Joseph Rothenberg, associate director of Hubble flight projects. This sets up a reaction in the telescope's supersensitive controls.

"The thing that causes the spacecraft to jitter is its own control system sensing errors and correcting," he said.

This flutter in turn sets up a second vibration that occurs randomly



BY JOHNSTONE QUINAN—THE WASHINGTON POST

for a minute or two at a time over periods of up to 20 minutes in sunlight.

The solar arrays were built for the European Space Agency (ESA) by British Aerospace Space Systems Ltd. in Bristol, England, with subsystems from Germany, Switzerland and elsewhere in Europe and were based on a design purchased from Hughes Aircraft Co., according to Robin Laurance, ESA's project manager for the Hubble.

"The main fault is in the analysis," he said in a telephone interview from Noordwijk, the Netherlands. "We didn't predict correctly the rate at which the boom bends."

The bending was expected to occur slowly, over several minutes, rather than within seconds, he said.

Engineers "still haven't got to the bottom of what's really happening. . . . We're studying whether the boom-bending can trigger a motion in the drum," Laurance said.

The "drum" contains a spring-loaded device that can furl and unfurl the solar arrays like giant window shades. Its reaction, or that of spreader bars that support the "shades," or both, may be the cause of the second jitter.

Engineers have said the telescope was designed with a pointing system so precise that if it were a laser mounted on the Capitol and fired at New York City, it could hit a dime on top of the World Trade Center. The vibrations caused by the solar panel wiggle the end of the telescope, at most, only 22/100,000ths of an inch, but that means the bull's-eye at 200 miles expands from a dime to a 10-inch pizza. The problem is even greater over vast astronomical distances.

To neutralize the first jitter, controllers at Goddard Space Flight Center in Greenbelt last month sent up new computer instructions that would tell the control system not to react to the bowing of the booms.

The new instructions "worked too well," however, according to Edward Weiler, chief National Aeronautics and Space Administration scientist for the Hubble. "We fixed the first problem so well, it made the spacecraft more sensitive to the second problem."

The instructions have been shut off again while an additional fix is developed. New instructions are not expected to be ready to send to the telescope's computer until at least mid-February. However, even if the instructions eventually fix the flutters, Rothenberg said, they would use up all of the on-board computer capacity and render it too busy to compensate for any unexpected operational problems. "It mortgages our future," he said.

For this reason, ESA engineers, in coordination with the U.S. team, are working on a redesigned set of solar panels that could be carried aloft by a shuttle in 1993. The new design includes thermal covers to prevent the booms from bending, Laurance said. They are also working on ways to repair the existing set.

"We'll weigh the risks of replacement versus fixing this one, but in any case we'll have a spare aboard the shuttle," Rothenberg said.

The advanced-technology aspects of the solar arrays are working, Weiler said. "They're producing power like crazy . . . more than we expected." The solar power is converted to electric power to run the telescope's five instruments.

Although officials say ESA and NASA are working well together now, the relationship has suffered strains, particularly over the devastating discovery in June of the flaw in the primary mirror. It was caused a decade ago, apparently when a technician at the plant of a Connecticut contractor used a measuring rod improperly, and subsequent tests and analysis failed to catch the mistake.

In 1993, shuttle astronauts are expected to replace the telescope's workhorse camera, the wide field/planetary camera, with an advanced model that will include a built-in correction—like a pair of eyeglasses—to neutralize the flaw in the mirror.

Weiler said engineers are also studying ideas that might allow the telescope's other instruments to compensate for the flawed lens, such as replacing one instrument with a robot that could hold the equivalent of eyeglasses in front of the apertures of the remaining instruments.

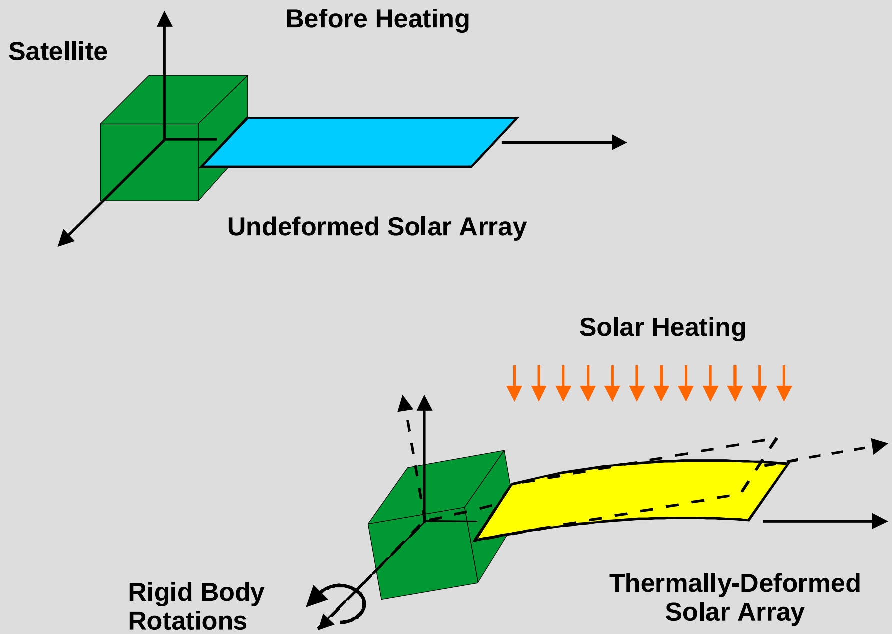
The Washington Post
November 11, 1990

Classification of thermally-induced dynamics

- Thermoelastic motions
  - Thermal snap (or Thermoelastic shock)
  - Thermally-induced vibrations
  - Thermal flutter

- Stick-slip motions
  - Thermal creak

Satellite attitude disturbances

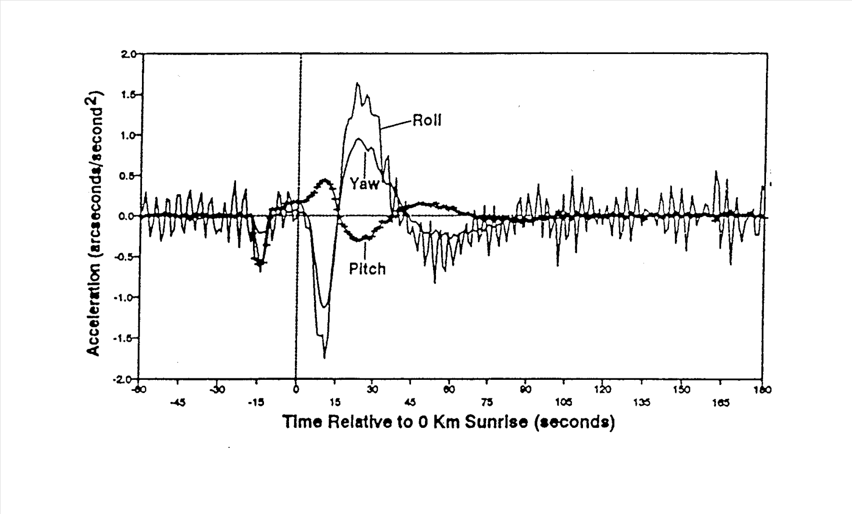


Example:
Solar array disturbance

- Booms/masts
  - OGO series (1960's)
  - IPEX II (1997)
- Flexible blanket solar arrays
  - Hubble Space Telescope (1990)
  - Space Flyer Unit (1996)
  - ADEOS (1997)
- Rigid panel solar arrays
  - TOPEX (1991)
  - Upper Atmosphere Research Satellite (1990)

Flight data

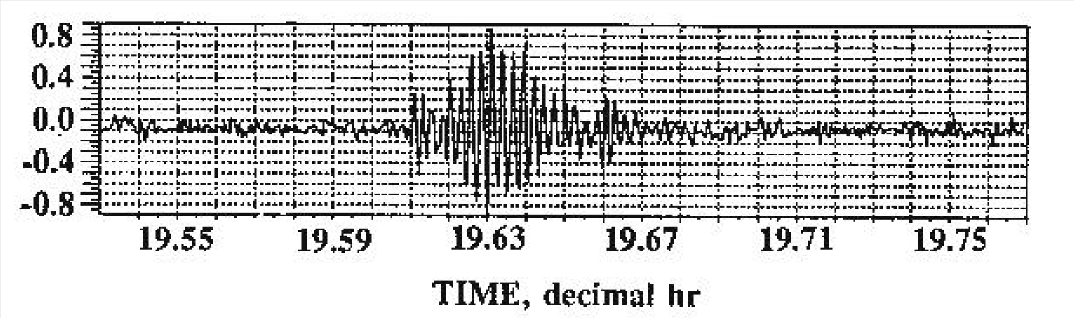
Thermal snap disturbance



UARS attitude acceleration (sunrise)

Reference: Lambertson, M., Underwood, S., Woodruff, C., and Garber, A., "Upper Atmosphere Research Satellite Attitude Disturbances During Shadow Entry and Exit," AAS 93-319, 1993.

Thermally-induced vibrations disturbance



HST attitude rate (sunrise)

Reference: Foster, C.L., Tinker, M.L., Nurre, G.S., and Till, W.A., "The Solar Array-Induced Disturbance of the Hubble Space Telescope Pointing System," NASA TP-3556, May 1995.

Previous research

- Boley (1956)
- Beam (1969)
- Zimbelman (1990)
- Thornton and students (1990's)
  - Kim, Chini, and Gulick
  - Foster, Blandino
  - Johnston

Research objectives

- Develop an understanding of thermally-induced structural motions of rigid panel solar arrays
- Develop analytical and computational models to predict solar panel thermal-structural performance
- Investigate interactions between thermally-induced motions of flexible appendages and satellite attitude dynamics
- Perform laboratory experiments

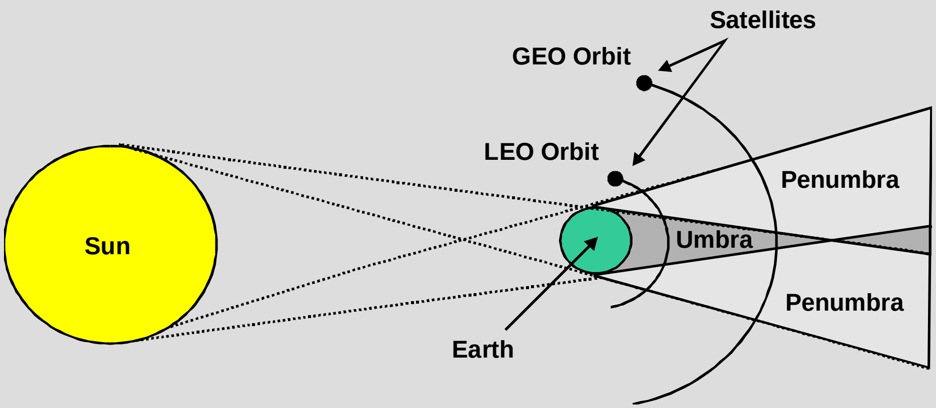
Analytical studies

- Orbital eclipse heating
- Appendage thermal response
- Appendage thermal-structural response
- Coupled satellite dynamics response

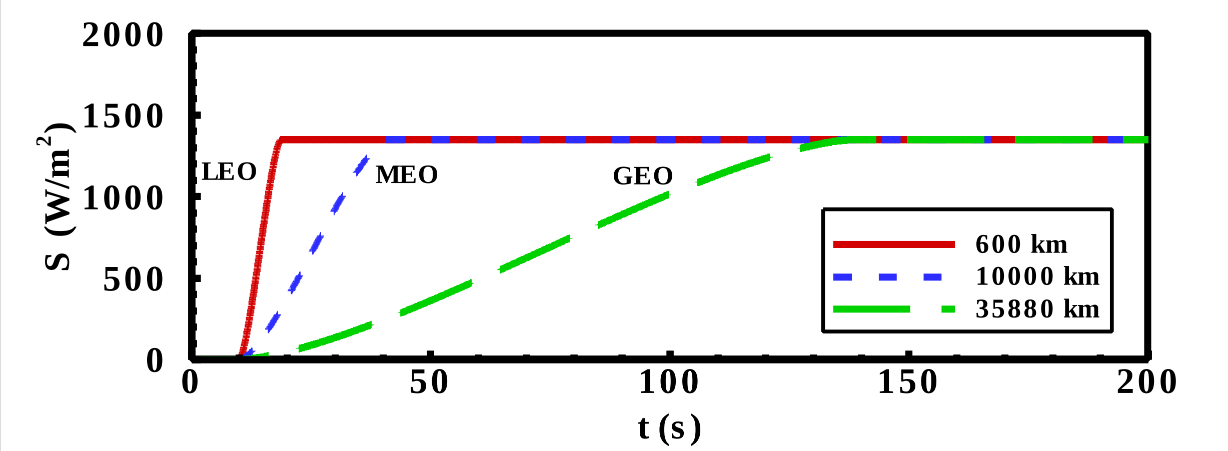
Orbital eclipse heating

Eclipse regions:

- Umbra (full shadow)
- Penumbra (partial shadow)



Solar heat flux vs time
(Sunrise eclipse transition)

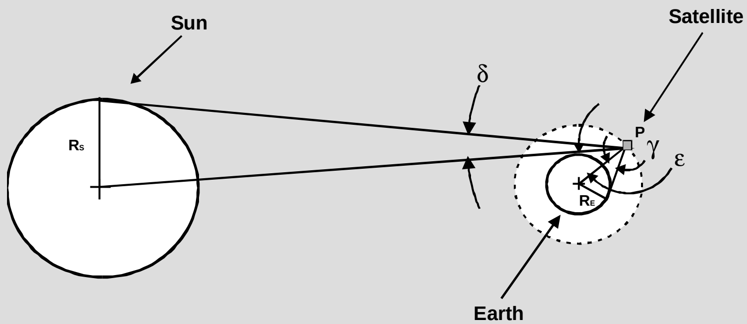


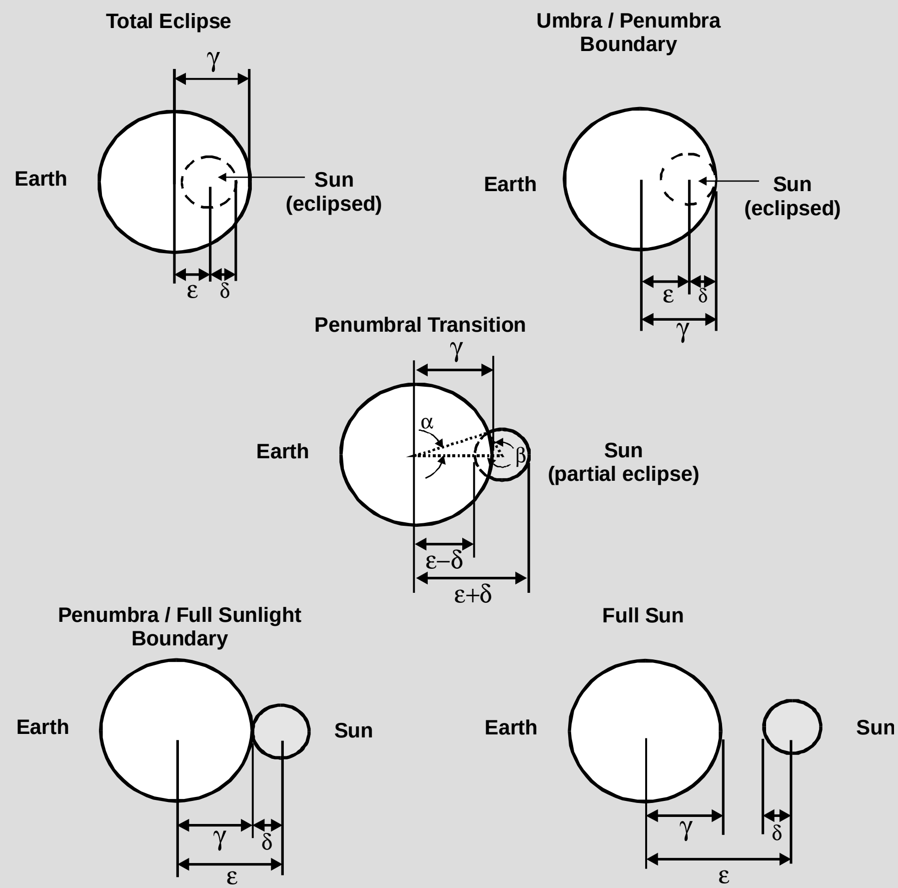
Approximate penumbral transition times:

LEO:	10 s
MEO:	30 s
GEO:	130 s

Penumbral heating calculation

Geometry of Sun/Earth disks as seen by satellite



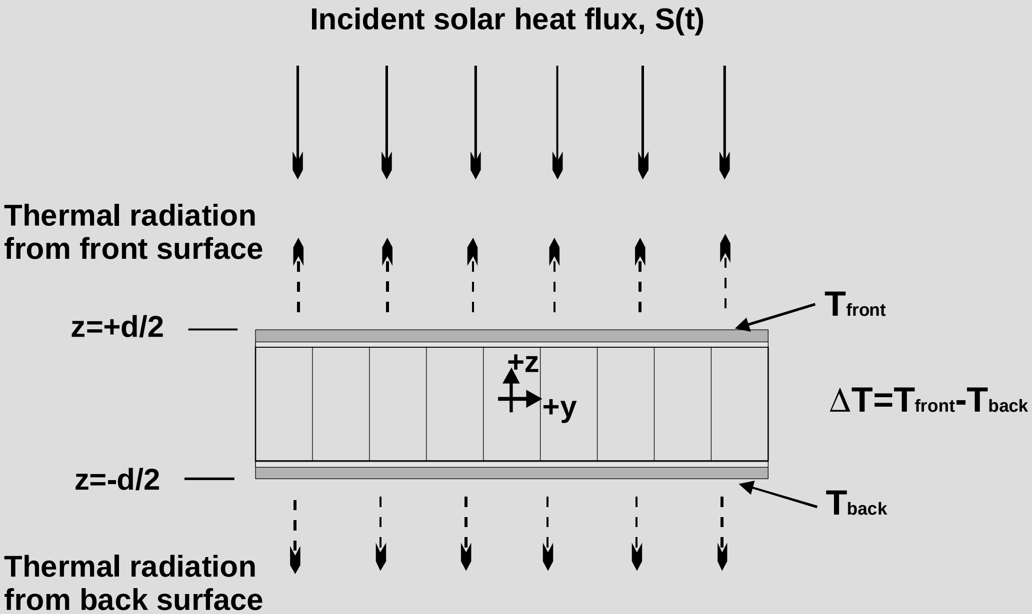


Incident solar heat flux is proportional to fractional area of Sun's disk visible to satellite

Reference: Baker, R.M., <u>Astrodynamics: Applications and Advanced Topics</u>, Academic Press Incorporated, New York, 1967.

Thermal analysis

- One-dimensional transient heat transfer model
- Time-varying incident solar heat flux from orbital eclipse heating analysis
- Solutions obtained using commercially available FEA program (ABAQUS)



$$rc\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2}$$

$$-k\left.\frac{\partial T}{\partial z}\right|_{z=+d/2} = se_{front}T^4 - a_{front}S(t)$$

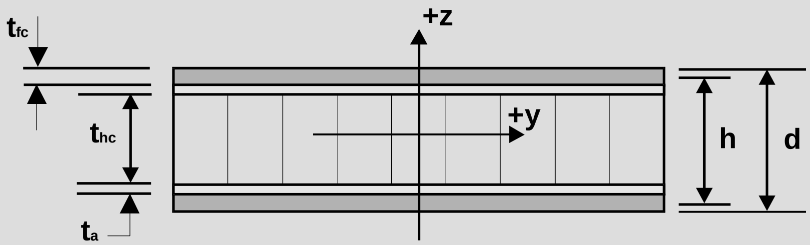
$$k\left.\frac{\partial T}{\partial z}\right|_{z=-d/2} = se_{back}T^4$$

Thermal-structural analysis

- Temperature distribution
  - Results from thermal analysis
  - Assume temperature varies through panel thickness only
- Thermal moment
  - Acts as forcing term in solar panel equations of motion
  - Enters problem through structural boundary conditions

$$M_T(t) = \int_A \left[E\alpha_{cte}\left(T(z,t) - T_{ref}\right) z \right] dA$$

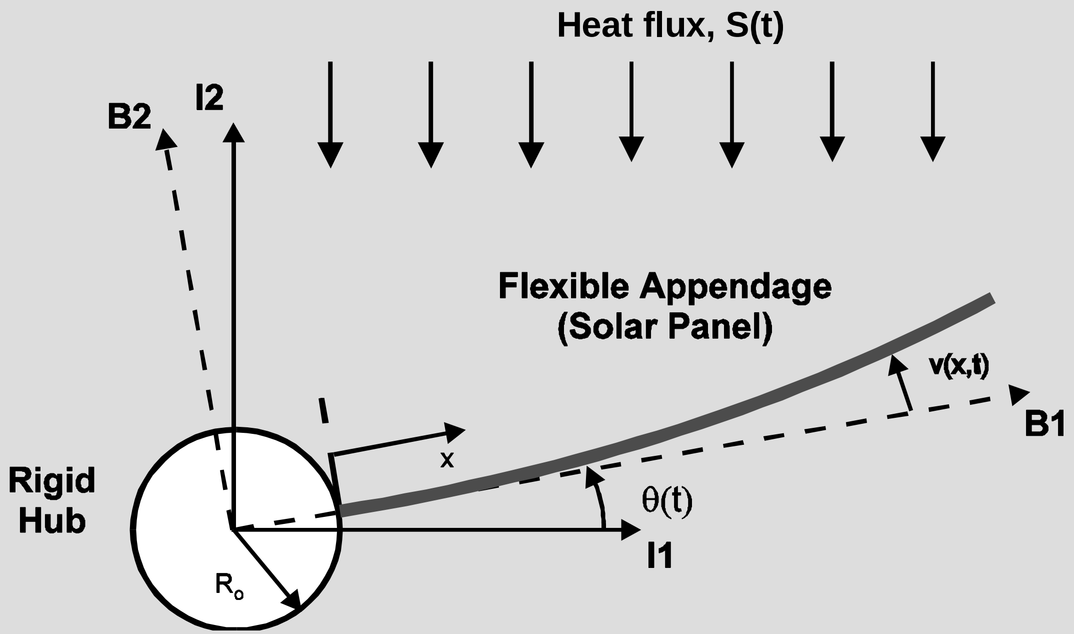
$$M_T(t) = E_{fc}\alpha_{cte,fc}\left(\frac{Wt_{fc}h}{2}\right)\Delta T(t)$$



Solar Panel Cross-section

Satellite dynamics analysis

- Simple satellite model: hub-appendage system
  - Rigid hub with cantilevered flexible appendage
  - Hybrid coordinate dynamical model
  - Only planar dynamics considered

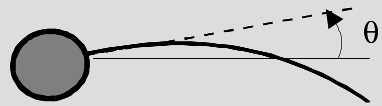


Problem formulation

- Energy methods approach
  - Start with kinetic and potential energies for system
  - Thermal terms enter through potential energy
- Governing equations
  - Generalized form of Lagrange’s equations used to obtain equations of motion and boundary conditions
  - Equations of motion for hub and appendage are coupled
- Solutions
  - Quasi-static
  - Dynamic

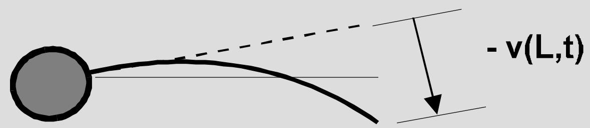
Equations of motion

Attitude angle, q(t):



$$I_{sc}\frac{\partial^2 q}{\partial t^2}+\int_0^L rA\left(R_o+x\right)\frac{\partial^2 v}{\partial t^2}\,dx=0$$

Appendage displacements, v(x,t):



$$rA\left(R_o+x\right)\frac{\partial^2 q}{\partial t^2}+rA\frac{\partial^2 v}{\partial t^2}+c\frac{\partial v}{\partial t}+EI\frac{\partial^4 v}{\partial x^4}=0$$

$$v(0,t)=0 \qquad \frac{\partial v}{\partial x}(0,t)=0$$

$$\mathrm{EI}\frac{\partial^2 v}{\partial x^2}(\mathrm{L},t)+\mathrm{M_T}(t)=0 \qquad \mathrm{EI}\frac{\partial^3 v}{\partial x^3}(\mathrm{L},t)=0$$

Discrete form of equations of motion

Assumed solution:

$$v(x,t) = v_{qs}(x,t) + \sum_{n=1}^{N} q_n(t) f_n(x)$$

, where : $v_{qs}(x,t) = -\dfrac{a_{cte}(1-n^2)\Delta T(t)}{2h} x^2$ = quasi-static solution

$q_n(t)$ = generalized modal coordinates

$f_n(x)$ = shape functions
(cantilever beam eigenfunctions used)

Discrete equations of motion:

$$[\mathbf{M}]\left\{\frac{\partial^2 \mathbf{x}}{\partial t^2}\right\} + [\mathbf{C}]\left\{\frac{\partial \mathbf{x}}{\partial t}\right\} + [\mathbf{K}]\{\mathbf{x}\} = \{\mathbf{F(t)}\}$$

, where : $\{\mathbf{x}\} = \{q, q_1, q_2, \ldots, q_N\}$

Disturbance torque

Equation of motion for rigid hub:

$$I_{sc}\frac{\partial^2 q}{\partial t^2} = -\int_0^L rA\left(R_o + x\right)\frac{\partial^2 v}{\partial t^2}\,dx = \mathrm{T}(t)$$

Disturbance torque due to appendage motions:

$$\mathrm{T}(t) = -\left[\mathrm{T}_{QS}(t) + \mathrm{T}_{DYN}(t)\right]$$

$$\mathrm{T}_{QS}(t) = \frac{rAa_{cte}\left(1-n^2\right)}{2h}\left(\frac{R_o L^3}{3} + \frac{L^4}{4}\right)\frac{\partial^2 \Delta T(t)}{\partial t^2}$$

$$\mathrm{T}_{DYN}(t) = rA\sum_{n=1}^{N}\left(\int_0^L \left(R_o + x\right) f_n(x)dx\right)\frac{\partial^2 q_n(t)}{\partial t^2}$$

Characteristic parameters

$B_r = \frac{t_r}{t_S}$ — **Revised Boley parameter**

$\mathrm{t_r}$ — **Temperature difference rise time**

$\mathrm{t_S}$ — **Period of fundamental mode of vibration for hub-appendage system**

$$\frac{v_{\max}}{v_{qs,\max}} = 1 + \frac{1}{\sqrt{1+B_r^{\;2}}}$$

Dynamic amplification factor

$\mathrm{B_r} >> 1.0$ — **Quasi-static response**

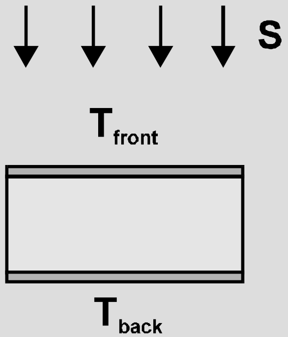
$\mathrm{B_r} \approx 1.0$ — **Thermally-induced vibrations response**

Numerical studies

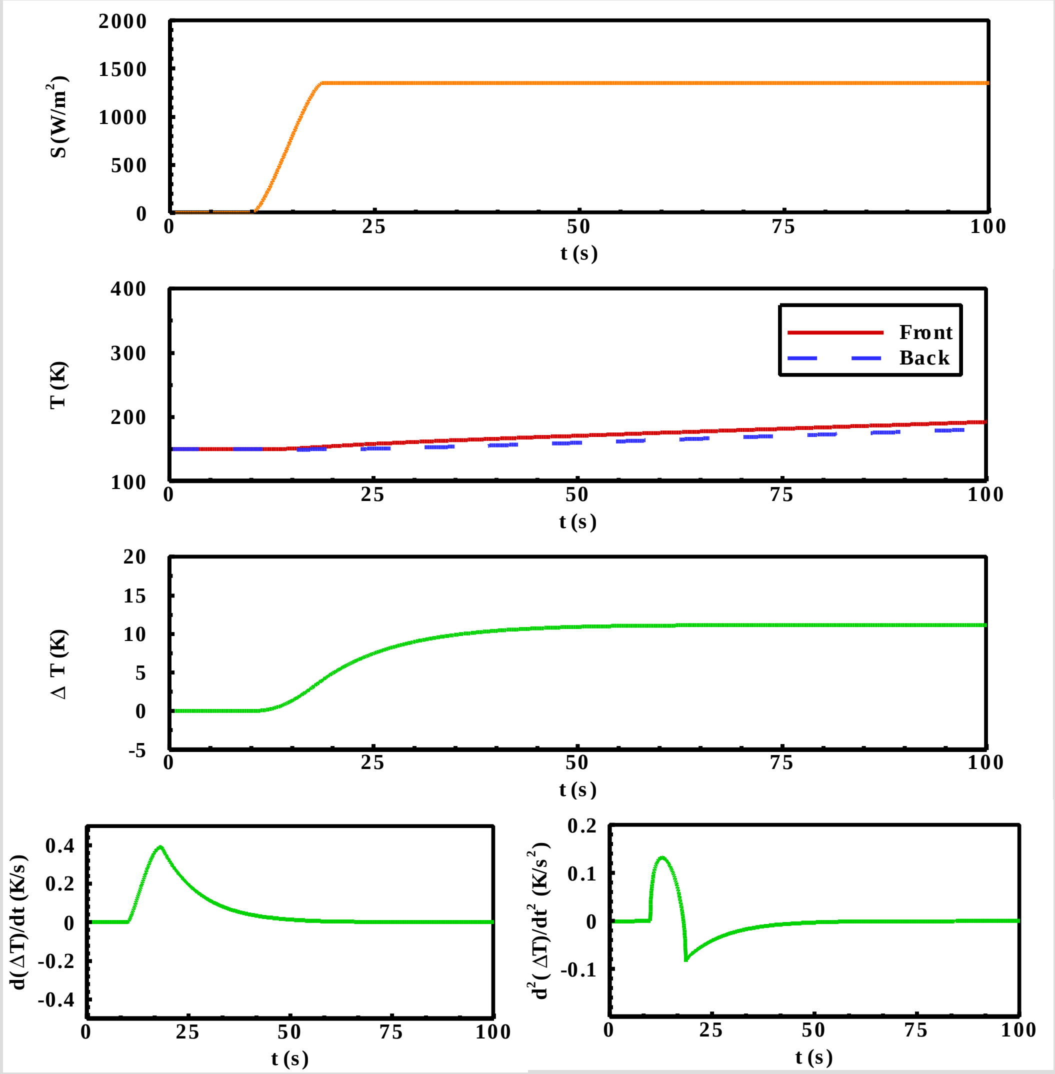
- Solar panel thermal response
  - Solutions obtained using finite element analysis
  - Results
    - Surface temperatures
    - Through-the-thickness temperature difference
    - Time derivatives of temperature difference

- Satellite dynamics response
  - Solutions obtained by numerical integration of discrete equations of motion using central differences method
  - Results
    - Flexible appendage displacements, velocity, and acceleration
    - Rigid hub rotation angle, angular velocity, and angular acceleration

Solar panel thermal response



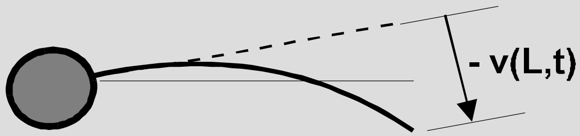
$\Delta T = T_{front} - T_{back}$



Parameters:
Sunrise eclipse transition
600 km circular orbit

Results:
$t_{penumbra}$ = 8.6 s
ΔT_{ss} = 11 K
t_{rise} = 60 s
Peak d(ΔT)/dt = 0.4 K/s

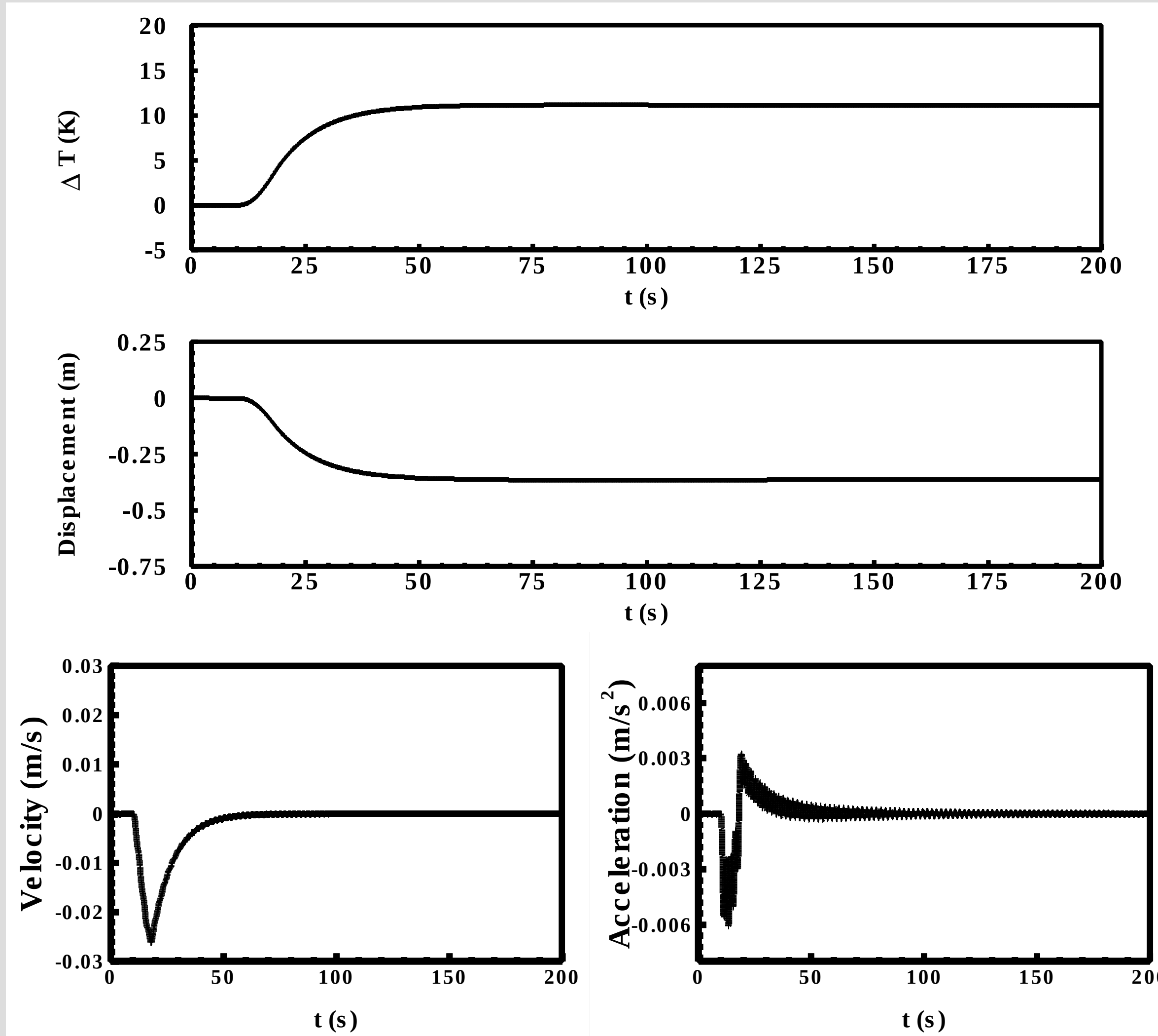
Flexible appendage response



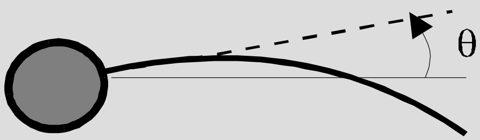
Appendage parameters:
L = 9m
W = 3 m
F_1 = 0.5 Hz (t_S = 2 s)
B_r = 30

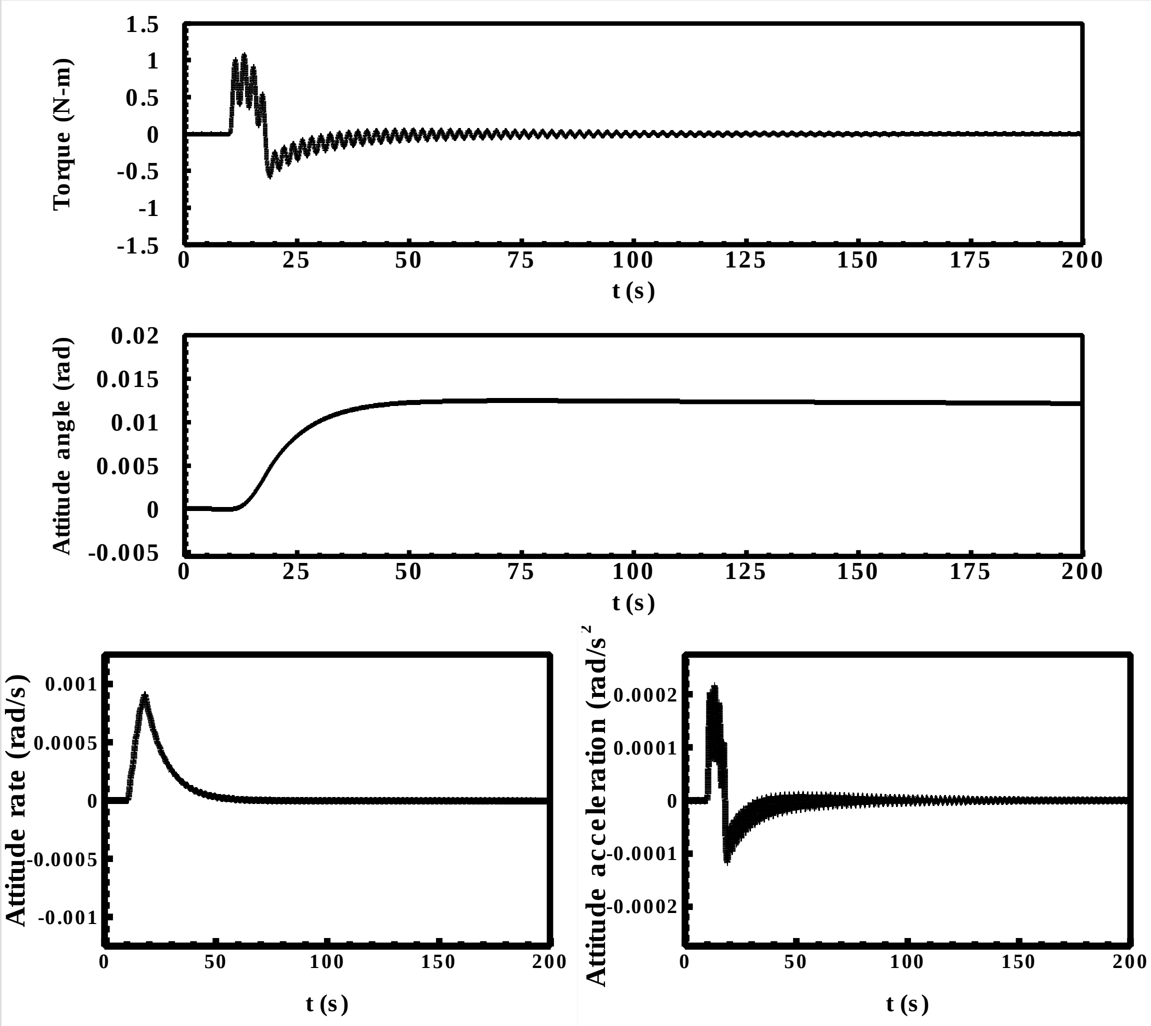
Results:
ΔT = 11 K
Tip displacement, v = -0.4 m
$v_{max}/v_{qs,max}$ = 1.0
Peak velocity = -0.03 m/s

Quasi-static response
Thermal snap transients



Rigid hub response





Hub parameters:

R_{hub} = 1 m

Mass = 5000 kg

$I_{hub}/I_{appendage}$= 1.0

Results:

Torque = 1/-.6 N-m

Attitude angle, θ = 0.01rad

$\theta_{max}/\theta_{qs,max}$ = 1.0

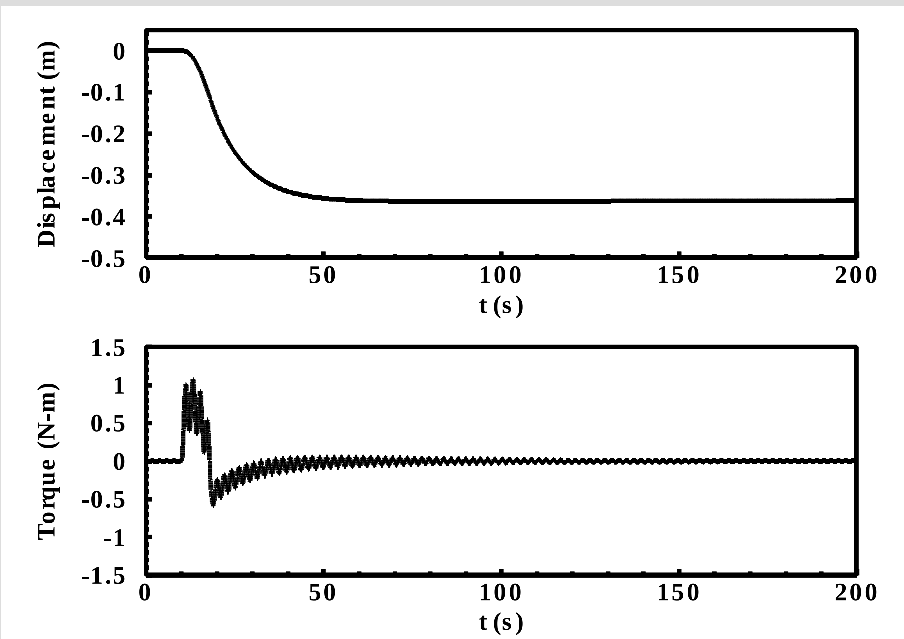
Attitude rate = 9E-4 rad/s

Thermal snap disturbance

Classification of thermally-induced dynamics

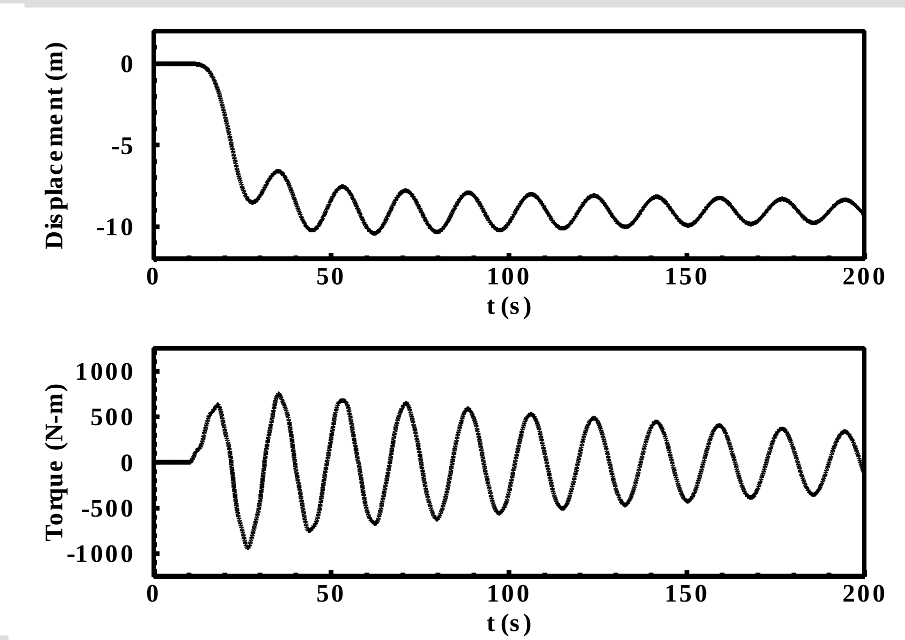
Thermal snap

t_r = 60 s
t_s = 2 s
B_r = 30
Maximum (v/v_{qs}) = 1.0



Thermally-induced vibrations

t_r = 60 s
t_s = 17 s
B_r = 3.5
Maximum (v/v_{qs}) = 1.2



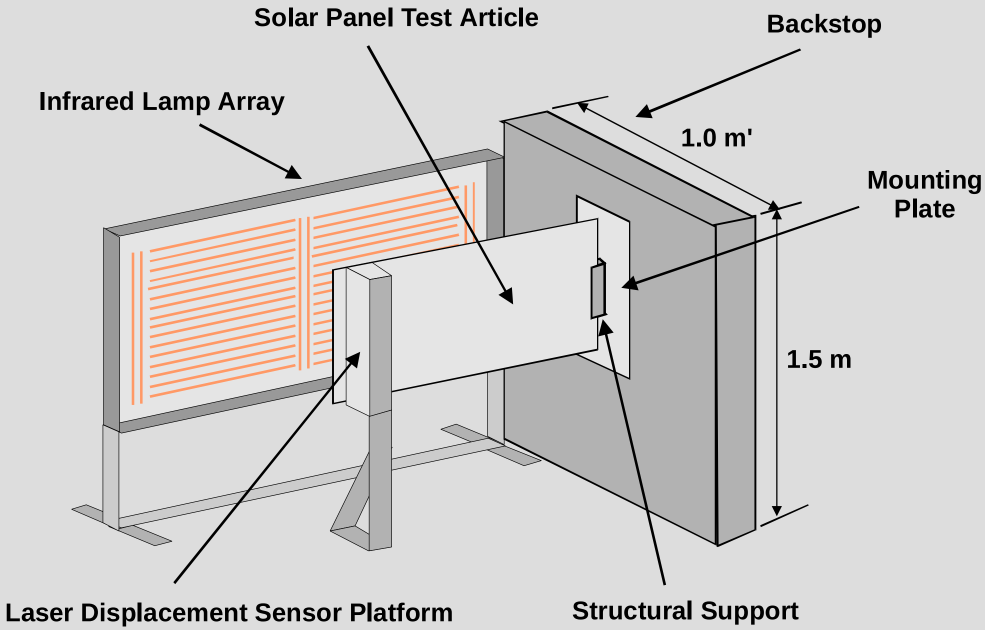
Experimental studies

- Objectives
  - Characterize the thermal-structural response of representative solar panel test articles
  - Investigate rigid panel solar array ‘thermal snap’ phenomenon
  - Study deployment hinge support effects
  - Provide data for validation of analytical models

- Test Articles
  - Honeycomb sandwich panels
    - High aspect ratio panel (L/W = 8)
    - Low aspect ratio panel (L/W = 2)
  - TRACE solar panel assembly

Laboratory test set-up

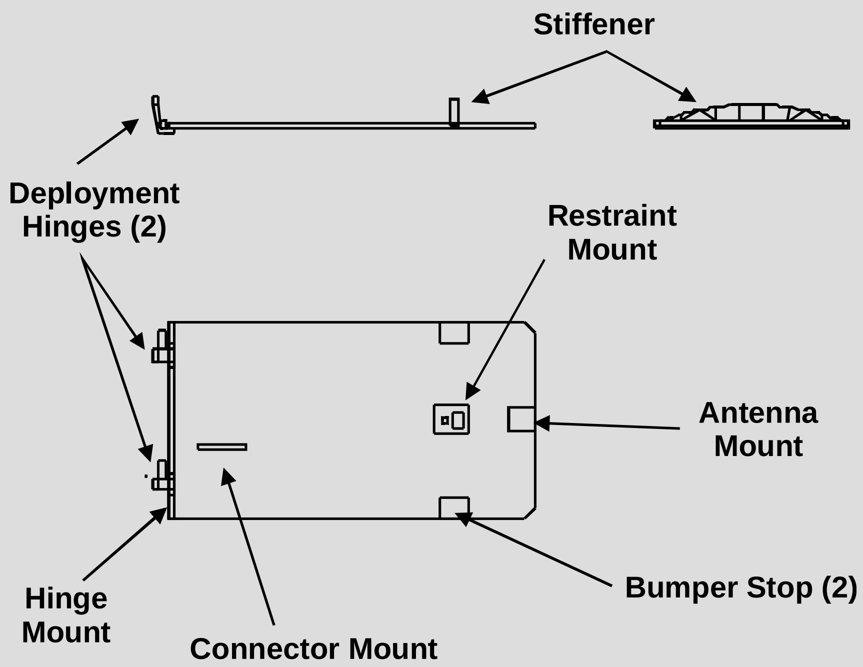
Schematic of test set-up

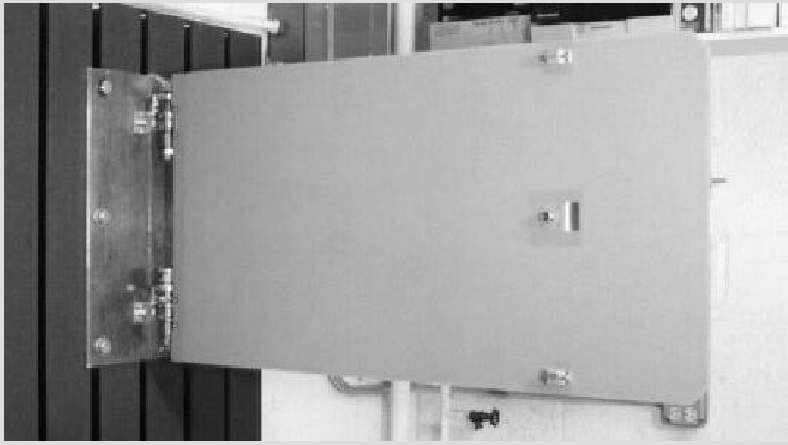


Photograph showing solar panel in test fixture

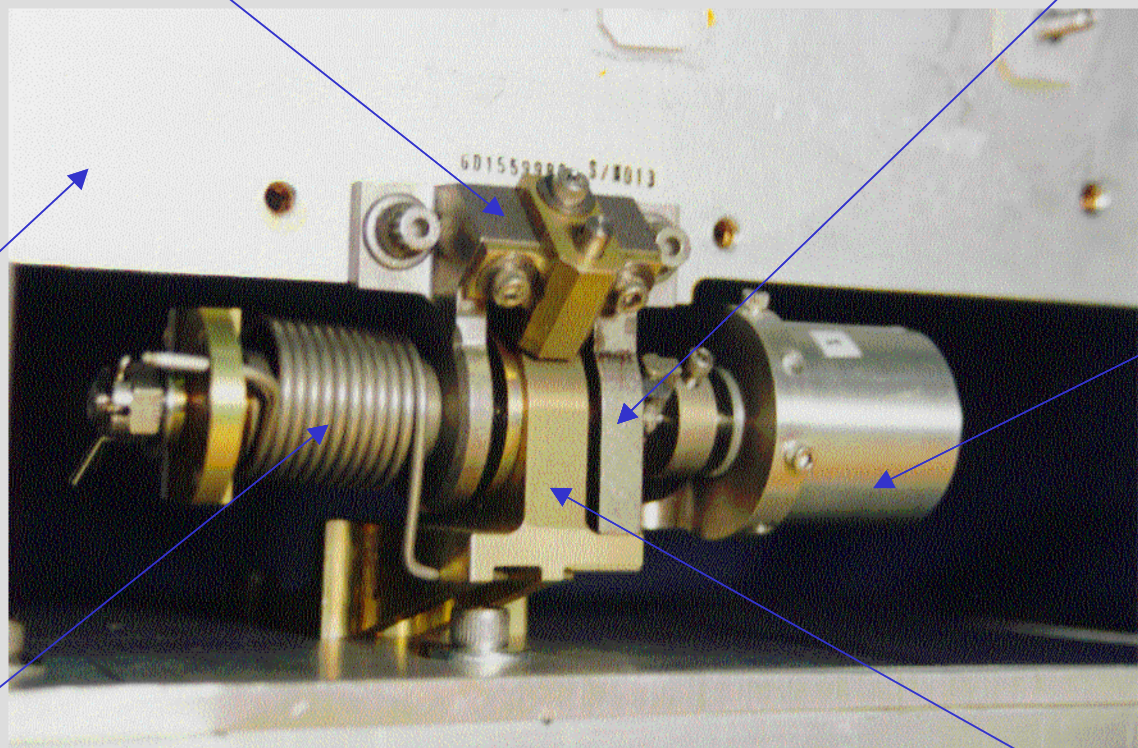
Solar panel test article

- ETU hardware from TRACE satellite
- Overall size: 1 m x 0.5 m
- Aluminum honeycomb sandwich panel substrate
- Deployment hinge supports



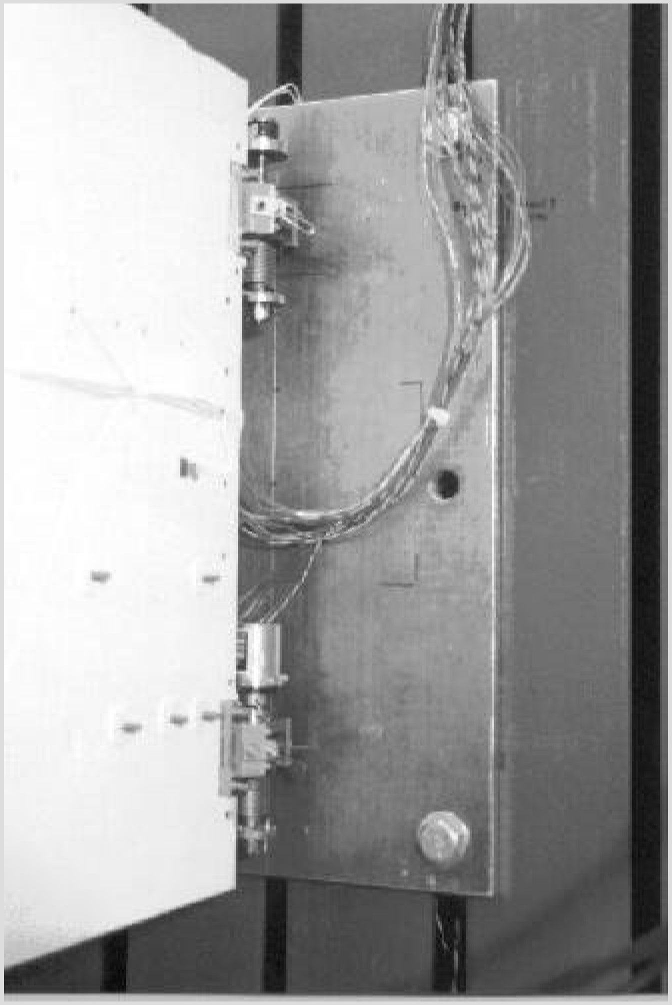


Deployment hinge

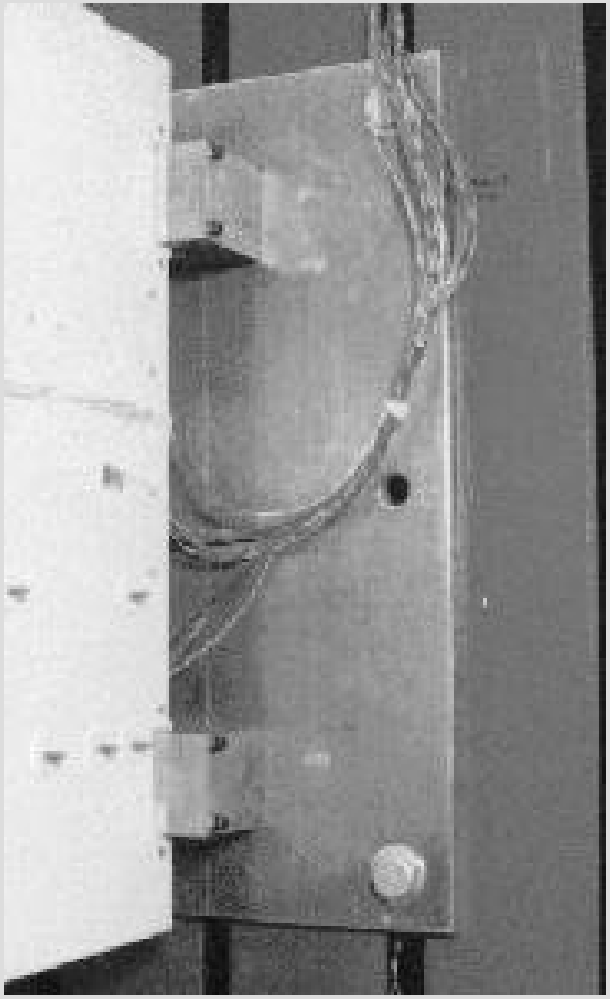


Structural supports

Deployment hinge supports

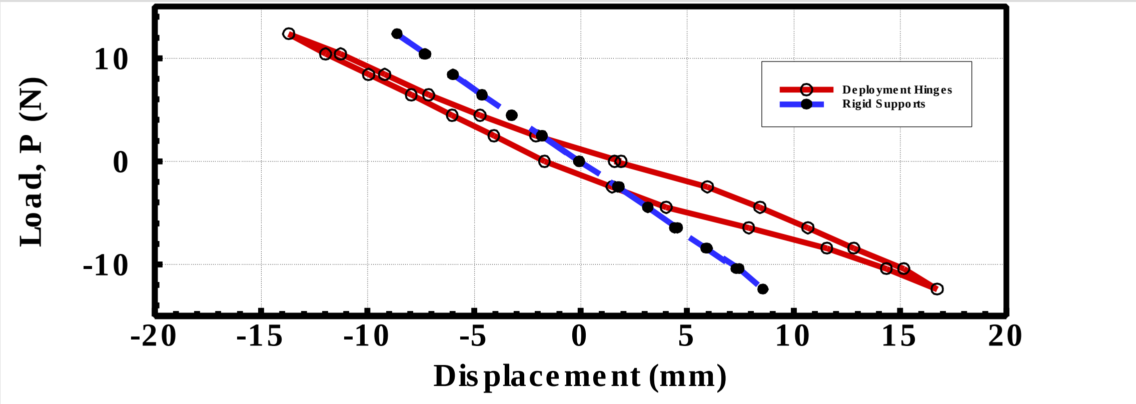


Rigid supports

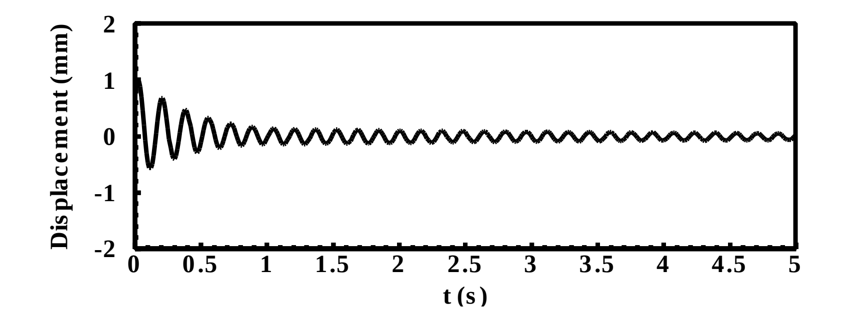


Support characterization tests

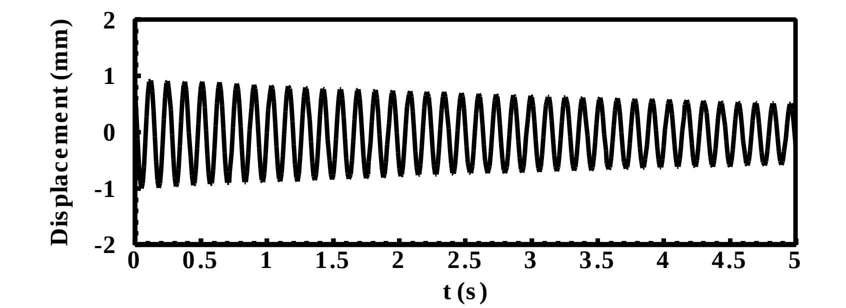
Point load tests



Free vibrations tests



Deployment hinge supports
F_1 = 6.3 Hz

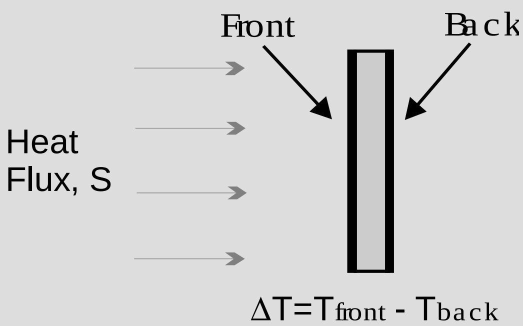


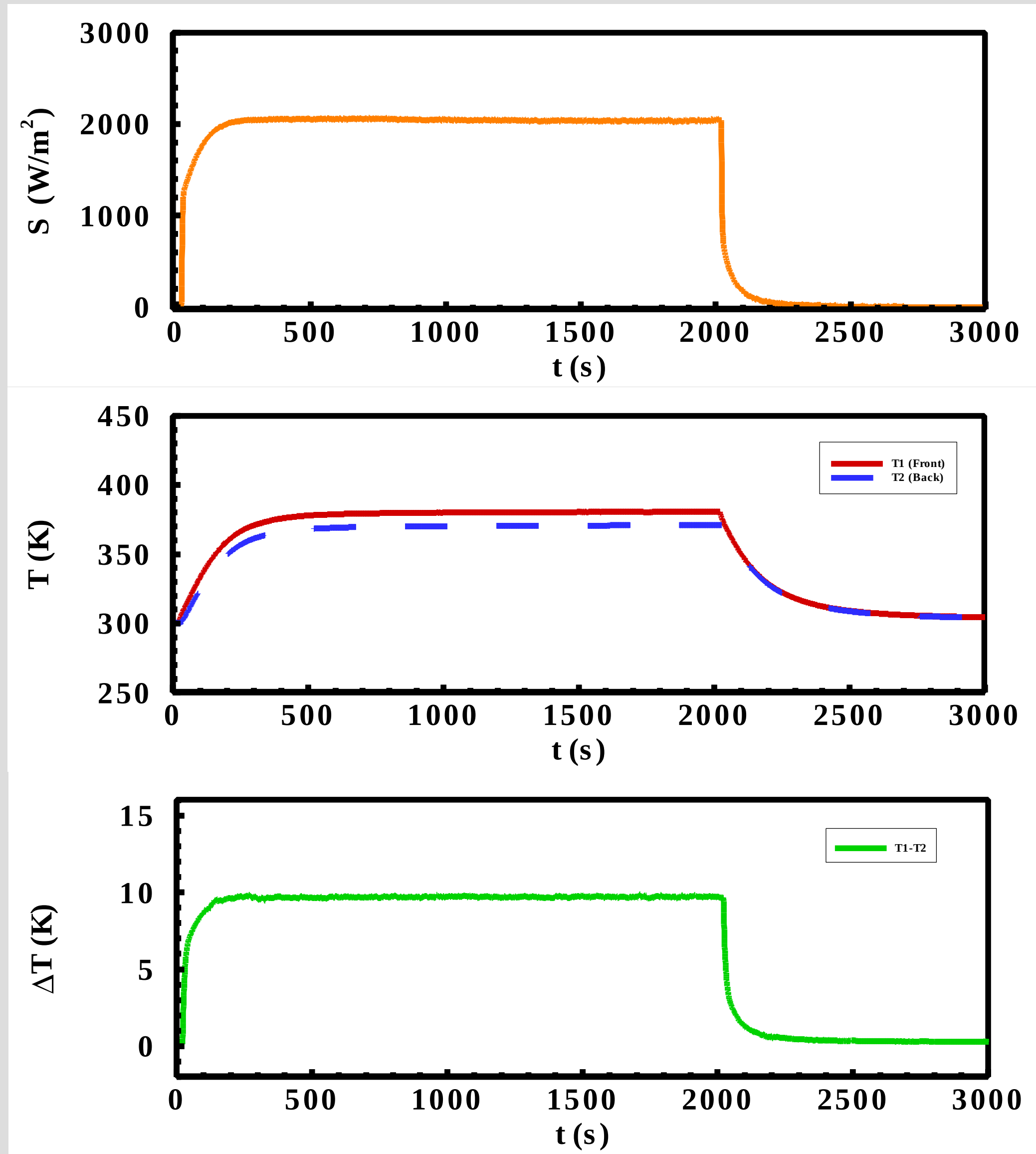
Rigid supports
F_1 = 7.6 Hz

Thermal response

Single Thermal Cycle Test

Time (s)	Event
0	Test begins
20	Lamp array on
2020	Lamp array off
3000	Test ends





Results:

$S = 2000\ W/m^2$

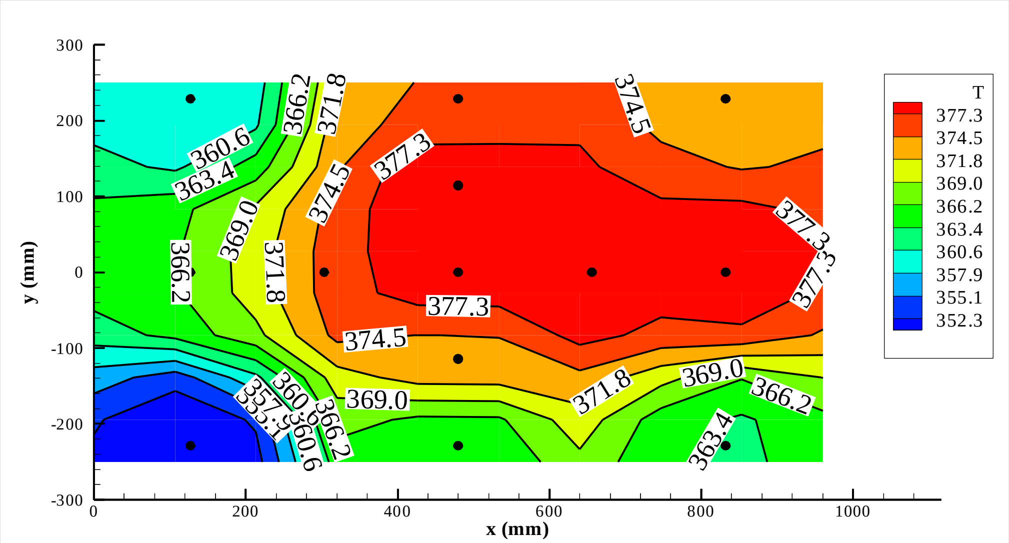
$T_{front} = 380\ K$

$T_{back} = 370\ K$

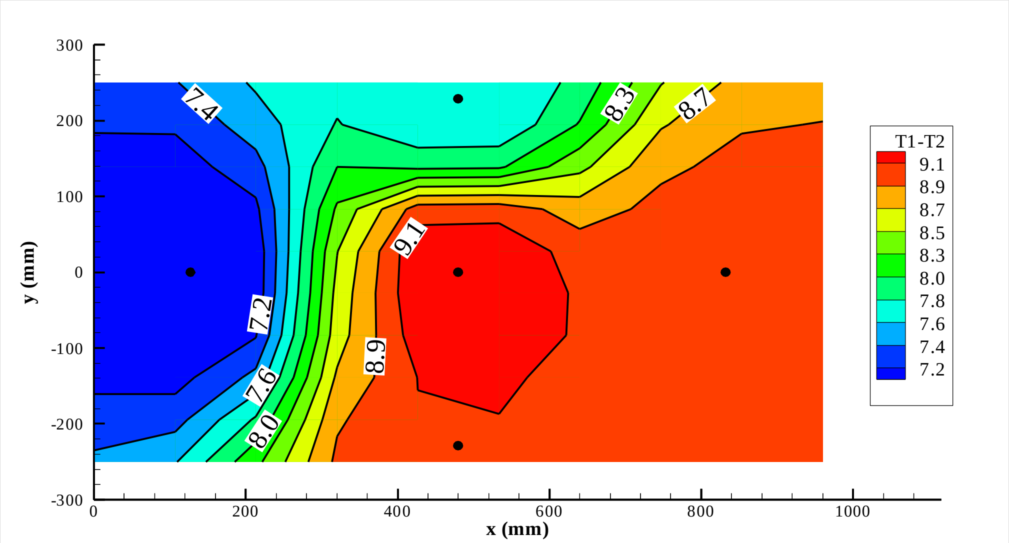
$\Delta T = 10\ K$

Thermal response - cont.

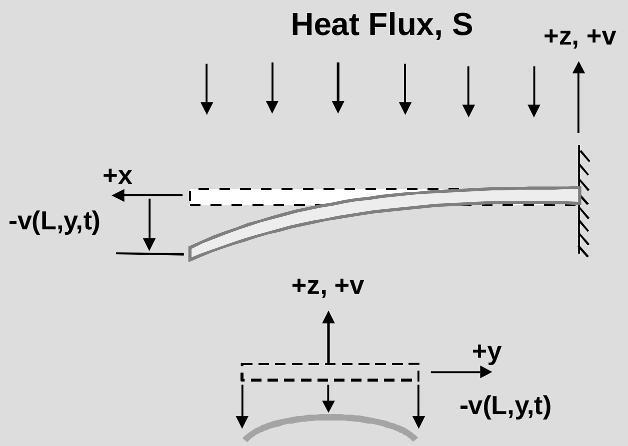
Front surface temperatures



Through-the-thickness temperature difference



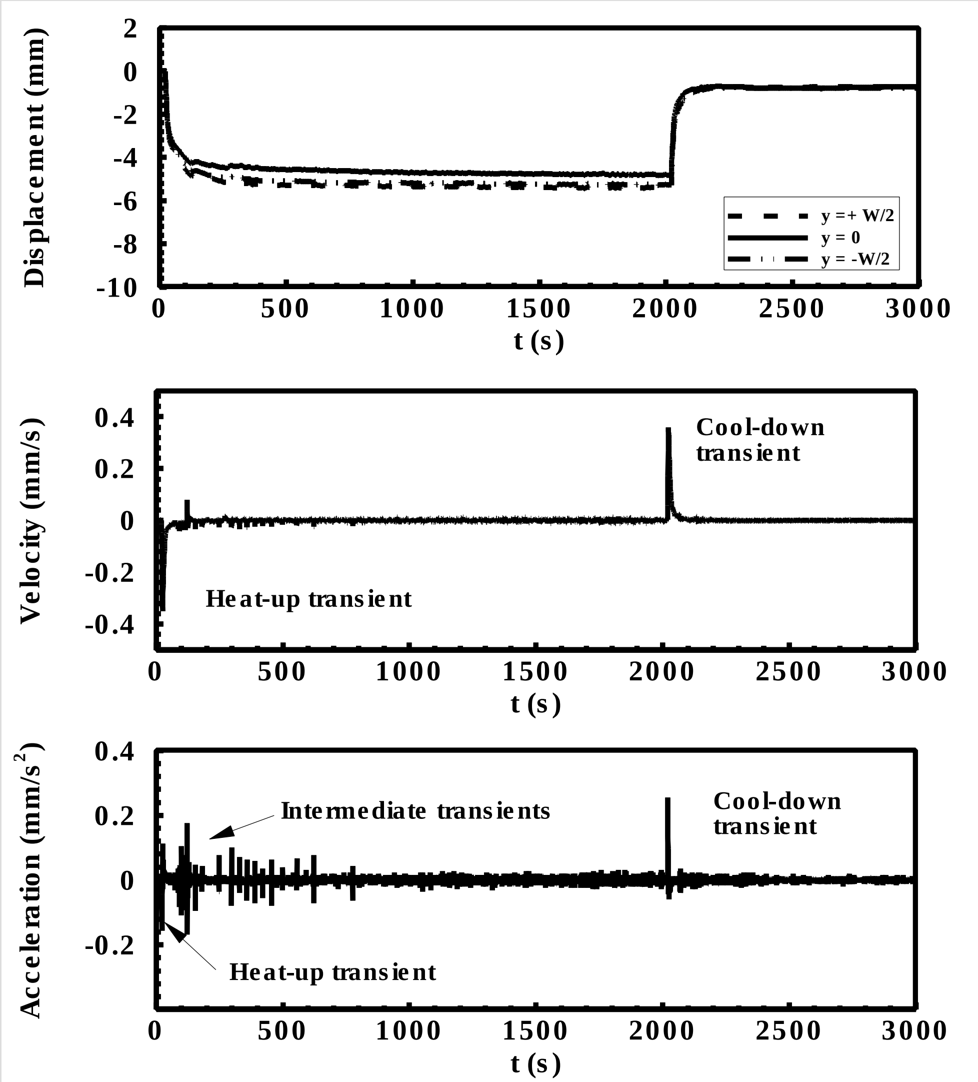
Structural response



Results at x=L:

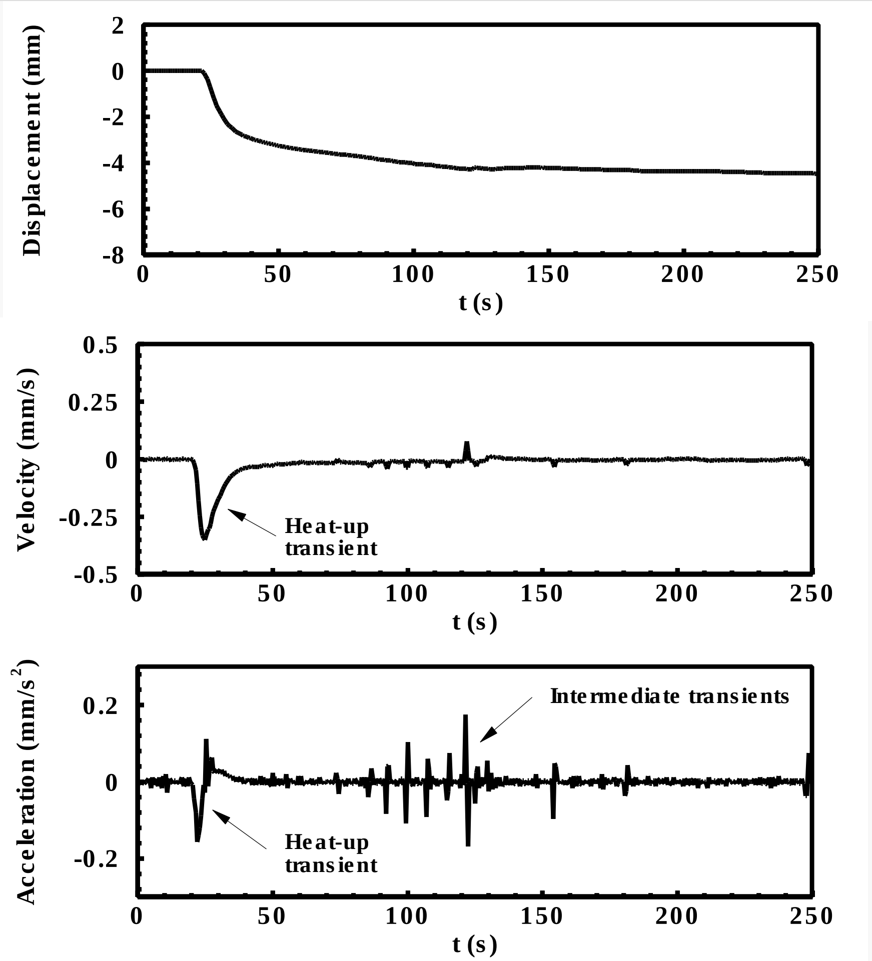
Displacement = - 5 mm
Velocity = 0.3 mm/s
Acceleration =0.2 mm/s^2

Quasi-static response
Thermal snap transients
Intermediate transients

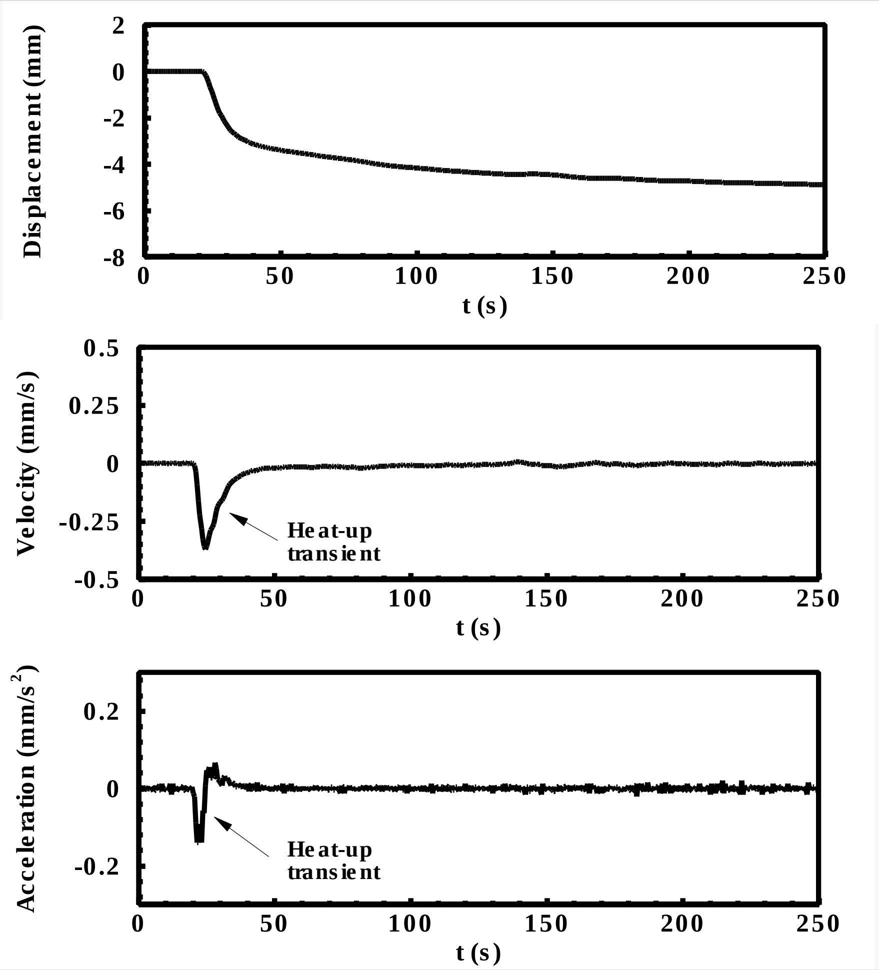


Effect of structural supports

Deployment hinge supports



Rigid supports



Analysis of experiments

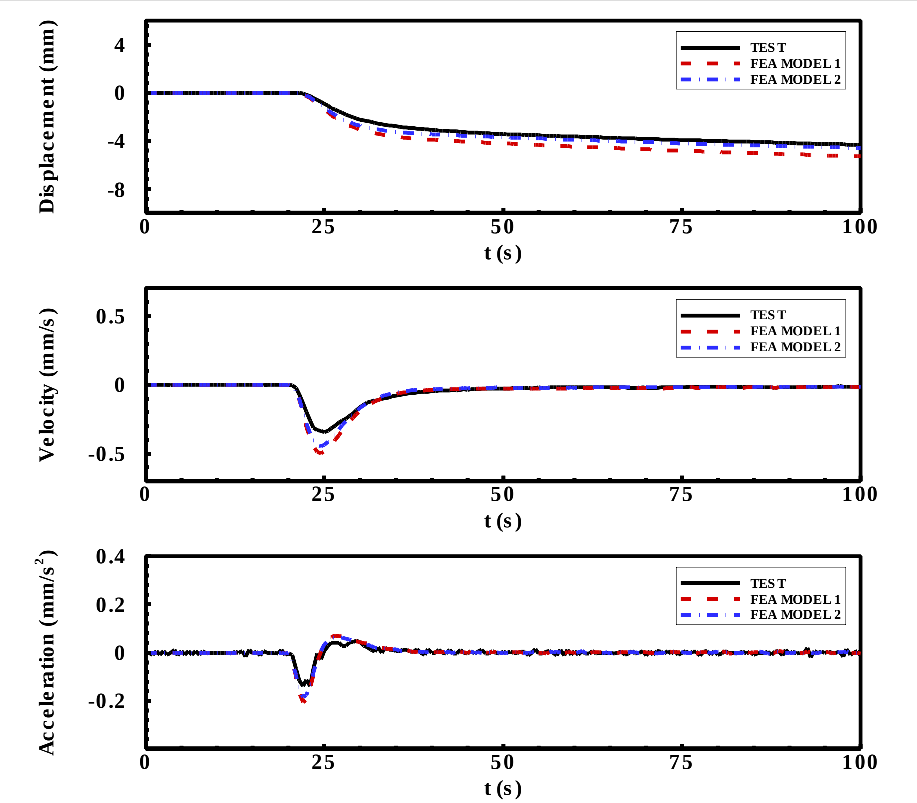
- Objective is to predict the thermal-structural response of the solar panel to simulated orbital eclipse transition heating.

- Finite element analysis
  - Solutions obtained using commercially available finite element program (ABAQUS)
  - Three-dimensional model required
    - Non-uniform radiant heating
    - Plate bending behavior
  - Utilized general purpose shell elements
  - Sequentially-coupled thermal-structural analysis using same mesh for both analyses
  - Predictions validated through comparison with test data

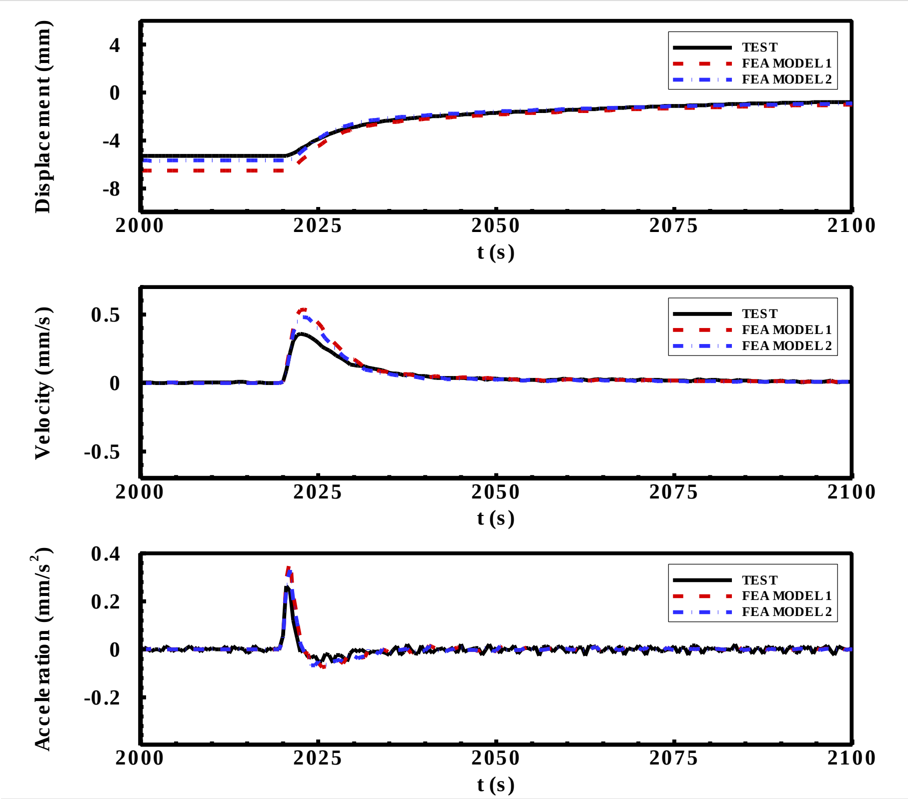
Comparison of analysis and experiment

TRACE solar panel structural response

Heat-up transient



Cool-down transient



Summary

- Thermally-induced dynamics of spacecraft structures are driven by time-varying temperatures distributions resulting from sudden changes in thermal loading.

- Classification of thermally-induced dynamics
  - A quasi-static response consists of rapid, non-oscillatory bending motions and results in a thermal snap disturbance.
  - Thermally-induced vibrations consist of a quasi-static deformation with superimposed stable oscillations and result in a harmonic disturbance at the fundamental frequency of the appendage. Thermal flutter is an unstable thermally-induced vibrations response.
  - Thermal creak disturbances result from thermally-induced stick-slip motions at frictional interfaces in mechanisms/joints.

Summary -cont.

- Analytical Studies
  - The temperature difference and its first and second time derivatives are key parameters for predicting thermally-induced dynamics.
  - The ratio of the temperature difference rise time and the period of the fundamental mode of vibration can be used to assess the potential for a thermally-induced vibrations response.

- Experimental studies
  - The TRACE solar panel test article exhibits a quasi-static structural response to simulated eclipse transition heating with thermal snap acceleration transients during heat-up / cool-down.
  - Deployment hinge nonlinearities influence solar panel thermal-structural behavior and result in thermal creak disturbances.
  - Three-dimensional finite element analysis is required to predict solar panel behavior accurately in the laboratory.

Further reading

- Texts

  - Thornton, E.A., Thermal Structures for Aerospace Applications, AIAA Education Series, American Institute of Aeronautics and Astronautics, Inc., Washington, D.C., 1996.
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- Dissertations

  - Zimbelman, D.F., "Thermal Shock and its Effect on Spacecraft Attitude Control," Ph.D. Dissertation, University of Colorado, Boulder, CO, 1990.
  - Foster, R.S., “Thermally-Induced Vibrations of Spacecraft Booms,” Ph.D. Dissertation, Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA, May 1998.
  - Johnston, J.D., "Thermally-Induced Structural Motions of Satellite Solar Arrays," Ph.D. Dissertation, Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA, May 1999.

- Journal articles and NASA documents

  - Boley, B.A., "Thermally Induced Vibrations of Beams," *Journal of the Aeronautical Sciences*, Vol. 23, No. 2, Feb. 1956, pp.179-181.
  - Beam, R.M., "On the Phenomenon of Thermoelastic Instability (Thermal Flutter) of Booms with Open Cross Section," NASA TN D-5222, June 1969.
  - Johnston, J.D. and Thornton, E.A., "Thermally-Induced Attitude Dynamics of a Spacecraft with a Flexible Appendage," *Journal of Guidance, Control, and Dynamics*, Vol. 21, No. 4, July-August, 1998, pp. 581-587.

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